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Metrological characteristics of an on-machine tool optical measuring system

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Abstract

Metrological characterisation is a fundamental step towards assuring the traceability of a measuring instrument; particularly challenging for non-contact optical imaging systems due to the inadequacy of a specific reference standard for establishing the accuracy and traceability of the optical systems. In this paper, we have determined the metrological characteristics of an optical system for on-machine milling tool measurement. The evaluation procedure is in reliance with ISO 15530 part 3. An artefact was manufactured by wire electrical discharge machining method from a traceable cylindrical gauge pin into a square end. The artefact was measured using a coordinate measuring machine, and the task-specific measurement uncertainty is determined. The artefact was then utilised to characterise the optical measuring system in actual operating conditions, on-machine in a production workshop environment. Experiments have shown the applicability of the procedure and the suitability of the proposed calibration artefact for characterisation of tool diameter and run out.

Keywords: Coordinate metrology, uncertainty, optical system, calibration artefact, machine tool.

1. Introduction

Accurate quantification of cutting tools geometrical parameters is of very high importance in precision machining processes as surface generation is obtained by offsetting the tool path according to the tool profile. Tool geometry can be measured off-machine using tool pre-setters, with the tool mounted on the tool holder. However, in such case, the clamping errors related to tool holder mounting on the machine tool spindle remain unknown leading to unquantified machining errors contributions. Thus, on-machine integrated traceable measurement systems are necessary to overcome the limitations and accomplishing reliable accurate tool measurements to attain precise machining processes. Furthermore, traceability of the quality assessment on machine tool before and after the machining process ensures a high production rate and reduce the cost of the manufacturing processes [1, 2].

Modern machine tools can be equipped with non-contact optical systems (laser beam interruption systems, laser scan micrometers and camera-based) for on-machine tool setting and tool monitoring [3-5]. However, traceability of such instruments is not guaranteed due to lack of the international standards [6, 7]. In this work, the performance of a high precision camera-based optical system is characterised using ISO 15530 part 3 which provides guidelines for evaluating the measurement uncertainty using calibrated artefacts or measurement standards [8]. For this purpose, an artefact was designed, manufactured, and calibrated using a coordinate measuring machine. The measurement procedure for the artefact calibration was defined and the uncertainty contributors from the calibration were quantified. Finally, the procedure for the camera-based optical system characterisation was defined and the instrument performance was quantified.

2. Methodology

The methodology resides on the designing and manufacturing of the artefact, defining the artefact calibration procedure and conducting verification tests on the tool measuring optical system. The details are provided in the following sections.

2.1. Optical system

Fig. 1 depicts the camera-based optical system CU2 Tool M67, produced by the company Conoptica AS, Norway, which is mounted on a Fanuc Robodrill α-D21LiB5adv, to perform measurements before and after machining operations. The system is designed to function inside the machine tool and is compatible with installation in areas contaminated by flood cutting fluid lubrication, metal chips from machining and air-born coolant droplets from oil mist lubrication. The system consists of a camera and an illumination unit and allows the automated inline tool measurement whilst spindle rotating at the desired speed for machining processes.

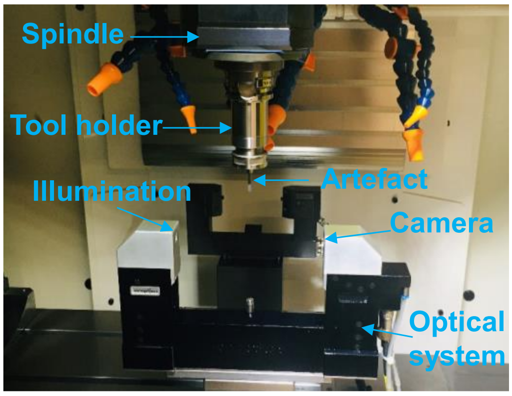

Fig. 1. Experimental setup depicting the optical system, artefact mounted on a tool holder and placed in the spindle.

The system has 160 mm sensor height, optical magnification x67, field-of-view 4.5 mm × 2.9 mm, and is suitable for measuring tools with tool diameter less than 4 mm. Fig. 2 depicts a schematic of the measurement procedure residing on moving the milling tool to the measuring position, illuminating from one side, and capturing images (over 200 in 4 seconds) of the rotating tool whereby millions of pixels show the contour of the milling tool at various rotation angles. The analysis is carried out in CU2 Tool software (provided by the manufacturer and integrated with the optical sensor) which uses the reference model information and the recorded images to establish the measurement results.

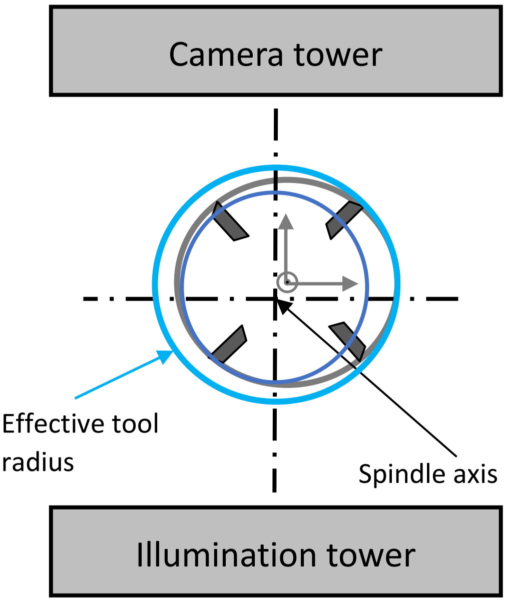

Fig. 2. Measurement principle of the optical system.

Each measurement cycle comprises of creating a reference model where each cutter is detected, digitally cleaned and parameters (e.g., radius and length) are determined. The effective tool radius is computed as the maximum radial distance relative to the centre of the spindle axis whilst the runout is determined as the difference between the largest and the smallest measured radii. The optical instrument is suitable for measurement of any types of end mills (e.g., flat, ball nose, corner radius, conical, form end mills). Basic measurement outputs are tool diameter, length, and runout of each cutting edge and corner radius [4].

This cost-effective, high-speed optical system is a step towards implementation of industry 4.0 with the aim of achieving reliable and accurate measurements. However, traceability of the measurement procedure is not established yet. Additionally, the optical system (CU2 Tool M67) is limited by the field of view; suitable for measuring the milling tool diameter (two-sided measurement) less than or up-to 4 mm. For this purpose, an artefact containing edge features like in an end mill, but with a simpler geometry enabling easy calibration, was designed to validate the instrument performance based on an internationally recognised standard (ISO 15530 part 3).

2.2. Calibration artefact: Design and manufacturing

An artefact was designed for characterising the tool measurement optical system. The design with a square end (Fig. 3) is chosen as the optical system is capable of measuring milling tools with sharp cutting edges. The nominal side length of the square

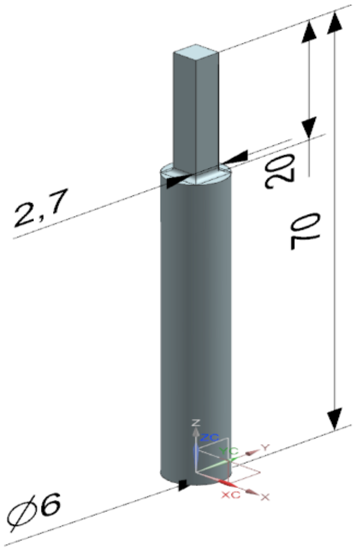

Fig. 3. CAD model of the calibration artefact with nominal dimensions in mm.

end is chosen to be 2.7 mm, yielding a nominal diagonal length of 3.818 mm to keep it consistent with the measuring range limitation of the optical system. The artefact was manufactured from a cylindrical gauge pin with a diameter of 6 mm ± 1 µm and length of 70 mm. The gauge pin was machined by means of wire electrical discharge machining (EDM) process on an AgieCharmilles CUT E 350 to obtain the square end (Fig. 3).

2.3. Coordinate measuring machine

Coordinate measuring machine (CMM) measurements were performed using CMM-001-Zeiss-PRISMO (MPE: (0.9 ± L/350) µm, L in mm) which serve as a reference [9, 10].

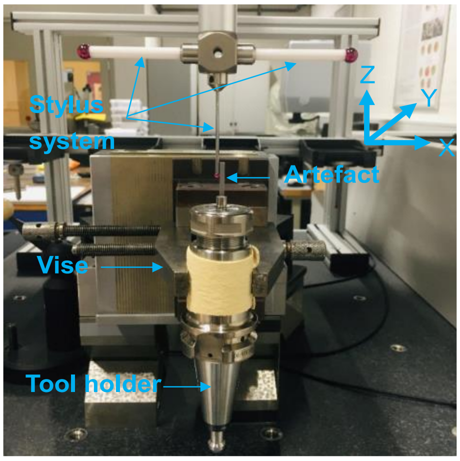

Fig. 4. Experimental assembly for CMM measurement.

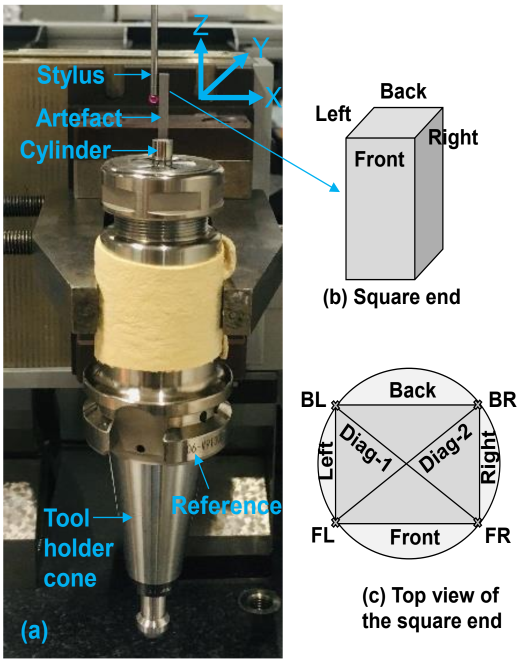

Fig. 5. (a) A close-up of the artefact mounted in the tool holder, (b) square end, and (c) top-view of the square end whereby FR, FL, BR, and BL represent front right, front left, back right and back left, respectively.

Fig. 4 shows a photograph of the experimental arrangement, the artefact is clamped on a vise which is fixed using accessories such as wedges, holders, and nuts. A T-shaped probe comprising of a vertical stylus with Ø3 mm (L: 58 mm) sphere and two horizontal styli with Ø8 mm (L: 63 mm) spheres was used. The ambient temperature during measurements was (20 ± 1) ºC, and the measurements have twenty repeats as stated in ISO 15530 part 3. The artefact was measured mounted in the tool holder (Fig. 5) and not removed from the tool holder after characterisation as this would affect the total runout of the tool-tool holder assembly every time the tool is removed and therefore prevent the use of the calibration measurements as a reference in the evaluation of the optical system.

2.4. Performance verification tests

The performance verification tests reside on ISO 15530 part 3 which provides a method of computing uncertainty in CMM measurements by utilising the calibrated artefacts or measurement standards [8]. The approach simplifies the uncertainty estimation pipeline by incorporating the similarity between the dimension and form/shape of the artefact and the calibrated artefact (reference). Hence, measurements are conducted similar to the actual measurements. In general, the ISO 15530 part 3 [8] takes into account four main uncertainty factors (associated with the random and systematic errors) contributing to the overall measurement uncertainty.

Thus, the expanded uncertainty, according to ISO 15530 part 3 [8], is defined by the following expression,

$$U_M = k\sqrt{u_{cal}^2 + u_b^2 + u_p^2 + u_w^2}, \qquad (1)$$

where k is the coverage factor; and set as $k = 2$ for 95% confidence of interval, u_{cal} is the standard uncertainty of the calibrated artefact, u_b is the standard uncertainty of the systematic error in the measurement procedure ($u_b = b$ when measurements are not corrected for systematic error, and $b = \bar{x} - x_{cal}$), u_p is the standard uncertainty associated with the measurement being performed on the calibrated workpiece ($u_p = \left(\frac{s}{\sqrt{N}}\right)$, s is the standard deviation and N is the number of measurements performed [11, 12]), and u_w is the standard uncertainty related to material and manufacturing changes of the measured object such as expansion coefficient, surface texture, and dimensional errors.

Considering the CMM probing and systematic error, the calibration uncertainty in the CMM measurements can be expressed as,

$$u_{cal} = \sqrt{CMM_{\text{rep}}^2 + CMM_{\text{probe}}^2 + CMM_{\text{scan}}^2 + CMM_{\text{system}(x,y)}^2} \quad (2)$$

$$= \sqrt{(0.06)^2 + (0.2)^2 + (0.7)^2 + (0.1)^2} = 0.74\ \mu\text{m} \quad (3)$$

where, CMM_{rep} is the uncertainty in the repeated CMM measurements, CMM_{probe} is the uncertainty due to probe qualification, CMM_{scan} is the scanning probe error, $CMM_{\text{system}(x,y)}$ is associated with systematic error in the x and y direction.

3. Experiments and results

Fig. 1 and Fig. 4 show the photographs of the experimental setup of the optical system and the CMM, respectively. An approach based on ISO 15530 part 3 is introduced to evaluate the performance of the optical tool measuring system. The technique relies on the uncertainty evaluation in the CMM measurement through a series of measurements (20 repeats recommended) and using that knowledge to conduct the verification tests (as described in section 2.4) on the optical instrument. To fulfil the similarity criteria, the artefact was mounted on a tool holder and CMM measurements were performed. The tool and tool holder assembly were later placed in the spindle of the CNC machine to conduct measurements of the artefact on the optical system (20 repeats).

The CMM measurement strategy comprised of estimating the cylindricity and cylinder diameter of the round shaft area protruding from the tool holder, flatness of planes and interplanar distances of the square end, coaxiality of square central axis with the cylinder axis and with the tool holder cone axis, and radius of the circle circumscribing the square at Z-height 0.2608 mm (Fig. 5, Fig. 6).

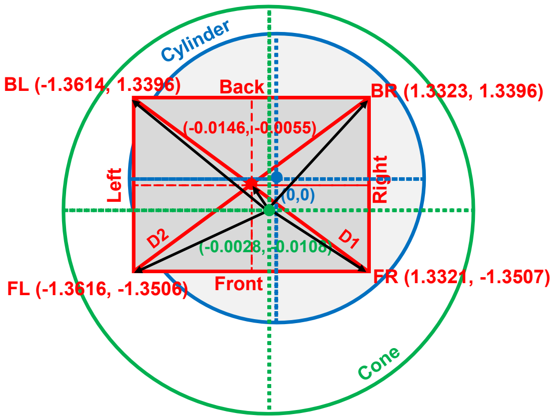

Fig. 6. Representation of the measured central coordinates of the cylinder, square end at 0.2608 mm (Z-height), and the cone (tool holder). The coordinates of the cone centre are with respect to the base alignment and shown for one of the CMM repeated measurements.

Table 1. Features of the calibration artefact measured by CMM.

Feature characteristic	Measured value (average of 20 repeats)	Repeatability (95% CI)	Feature characteristic	Measured value (average of 20 repeats)	Repeatability (95% CI)
Cylinder diameter	5.9995 mm	0.01 µm	Coaxiality Square vs Cylinder	20.51 µm	0.28 µm
Cylindricity	1.76 µm	0.023 µm	Coaxiality Square vs Cone	22.21 µm	0.08 µm
Flatness XZ Front	1.71 µm	0.014 µm	Coaxiality Cylinder vs Cone	3.06 µm	0.09 µm
Flatness YZ Right	1.17 µm	0.022 µm	Distance Front-Back	2.694 mm	0.05 µm
Flatness XZ Back	1.13 µm	0.02 µm	Distance Left-Right	2.696 mm	0.03 µm
Flatness YZ Left	1.13 µm	0.02 µm	Distance D1@-0.2608	3.8070 mm	0.09 µm
Flatness XY Top	0.46 µm	0.023 µm	Distance D2@-0.2608	3.8072 mm	0.09 µm
Temperature	20.03 °C	0.02 °C	MinCircum circle@-0.2608	3.8031 mm	0.07 µm

Table 2. Artefact geometry based on the virtual plane approach.

Edge name	Distance from the tool holder centre to the edge of the square circumscribing circle (Mean of 20 repeats) /mm	Corner radius (Mean of 6 µm ROI) /µm	Radius of square circumscribing circle with corner radius consideration /mm	Repeatability (95% CI)	Difference from Conoptica (R: 1.9162 mm) /µm	Runout (Diff btw largest and smallest radii) /µm
Back Right (BR)	1.8989	8.925	1.8989 - 0.003697 = 1.8952	0.56 µm	1.9162 – 1.9129 = 3.3 µm	23.7 µm
Front Left (FL)	1.9081	7.813	1.9081 - 0.003236 = 1.9049	0.13 µm		
Back Left (BL)	1.9155	6.199	1.9155 - 0.002567 = 1.9129	0.12 µm		
Front Right (FR)	1.8916	5.601	1.8916 - 0.00232 = 1.8892	0.10 µm		

Before the measurement process starts, the CMM was initialised by performing probe configuration and probe qualification according to the manufacturer's specification and the same process was repeated at the end of the 20 repeated measurements.

The reference coordinate system of the calibration artefact was defined with respect to the square top plane as XY plane (Fig. 5(a-b)) with Z-direction pointing upwards. For the base alignment, four points on the square top plane, four points on a line defined on the front face of the square, and two complete circles (two different heights) around the cylinder were considered. The detailed measurements of the features of interest were performed by characterising each individual feature independently, and the outcome of these measurements is listed in Table 1.

The artefact radius is computed using the virtual plane approach. A theoretical plane is defined at Z-height 0.2608 mm (away from the top plane of the square end), and the intersection point of the theoretical plane placed at 0.2608 mm and the two adjacent outer tangential orthogonal planes (BR, FL, BL, FR) is determined. The radius of the square circumscribing circle (Z-height 0.2608, away from the top plane) is measured from the centre of the tool holder to the edge of the square end (Fig. 6 depicts the scenario for one measurement), and the outcome of the CMM measurements is given in Table 2. The runout is computed as the difference between the largest and smallest measured radii.

Additionally, the corner radii were measured by an optical microscope (Alicona CMM-005-Bruker, Infinite Focus G4, with 50x magnification). The traceability of Alicona is ensured by the calibration and verification certificate which uses Alicona's calibration tool (IF-Calibration Tool) to determine the measurement quality of the instrument by establishing the lateral, vertical and roughness calibrations. Thus, the optical microscope is calibrated with standardised and certified calibration tools which guarantees the accurate and efficient use of the measuring instrument. Consequently, the uncertainty contribution for 50x magnification is low and neglected. Further processing is performed in Scanning Probing Image Processor (SPIP) software. For that, a region-of-interest of 6 µm (average of 9 lines) is chosen and the curvature feature is utilised to quantify the edge radius.

Table 3 shows the results of uncertainty evaluation (following the pipeline stated in ISO 15530 part 3 and using equations (1-3)) which comprises the radius of the circle circumscribing the square at 0.2608 mm Z-height computed from the top plane of the square, as this is the height where the tool radius is measured by the optical system. The radius of the circle circumscribed to the square is computed by finding the distance from the center of the tool holder to the edge of the square end (given in Fig. 6). The largest measured radius of the square end is regarded as the artefact's radius (Back Left edge, Table 2) and the difference between the largest and smallest measured radii is the runout (Table 2). Furthermore, alternative solutions of characterising the reference artefact are in progress.

Subsequently for the optical system, each measurement cycle consists of making a reference model and the artefact measurement simultaneously (mentioned in section 2.1), and the process was repeated 20 times. The output of the optical sensor with respect to the diameter is twice the radial position of the cutting edge (milling tool) furthest away from the axis of rotation.

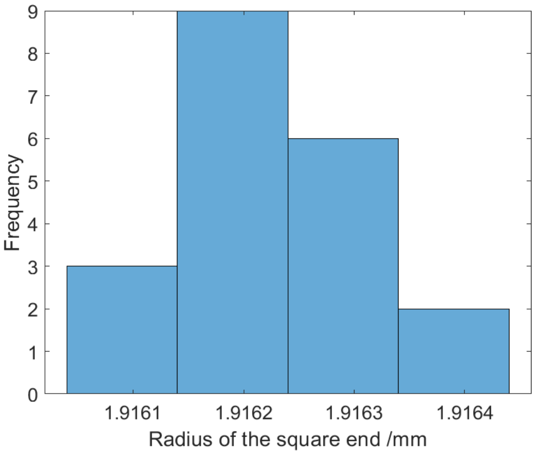

Fig. 7. Statistical distribution of the measured radius of the square circumscribing circle of the calibration artefact.

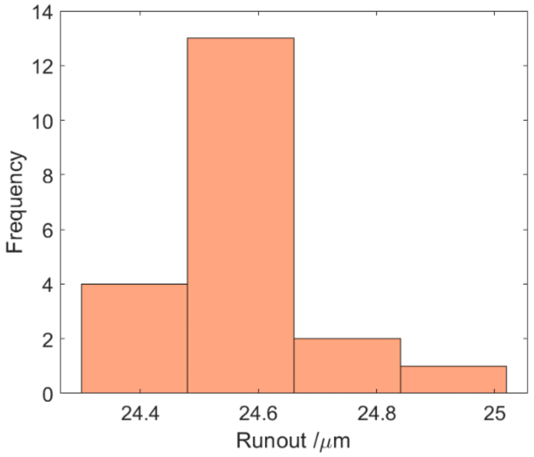

Fig. 8. Statistics of the measured runout by the optical system. The runout value is multiplied by two, as specified in ISO 1101 [13].

After measuring the radial position of each cutting edge with respect to the rotation axis, the sensor calculates the difference between the largest one and the smallest one to get runout value and divides the number by two to make it one-sided runout. This value is multiplied by a factor of two to make it according to ISO 1101:2017 standard [13] and compared with the CMM results. Thus, the uncertainty budget for the measured radius of the square circumscribing circle is established and the statistical distribution of 20 repeated measurements is shown in Fig. 7. Likewise, the statistics of the runout measured by the optical sensor is depicted in Fig. 8. Table 3 summarises the measurement results of the tool optical system.

Thus, the calibration artefact's radius (radius of square circumscribing circle at Z-height 0.2608 mm) measured by the optical system (1.9162 mm), and the runout (24.6 µm) have an expanded uncertainty of 6.8 µm and 2.3 µm, respectively, and quoted within 95% coverage interval (coverage factor k=2). The two measurements (artefact's radius and runout) are less prone to scaling error as measured on the same scale; however, the error resides on how precise the reference measurement is from the centre of the tool holder. From the 20 measurements performed with the optical sensor, it is clear that there is a systematic error (bias) in the measurements by the optical system. If this contribution is compensated, the measurement uncertainty of the optical system would be greatly reduced to approximately 1.5 µm (95% coverage interval). An investigation on the source of the systematic error is ongoing.

Table 3. Measurement results of the optical system.

Type	Artefact radius /mm	Runout / µm
Mean value	1.9162 mm	24.6 µm (One-sided runout × 2)
$\boldsymbol{u_{cal}}$	0.74 µm	0.74 µm
$\boldsymbol{u_b}$	3.3 µm (1.9162 - 1.9129)	0.9 µm (24.6 – 23.7)
$\boldsymbol{u_p}$	0.039 µm	0.032 µm
$\boldsymbol{u_w}$	insignificant	Insignificant
$\boldsymbol{U_M(k=2)}$	6.8 µm	2.3 µm

4. Conclusions and future work

In this work, the performance verification of a high-speed camera-based optical system for on-machine cutting tool measurement has been accomplished by employing the ISO 15530 part 3. Based on the similarity criteria, a calibration artefact was designed using a traceable workpiece (gauge pin) and validated by CMM measurements. The artefact was used for the task-specific uncertainty evaluation of the optical system; whilst the resulting outcome is compared with the reference measurement (CMM). The expanded uncertainty in the measured radius of square circumscribing circle is $U_M = 6.8$ µm (95% coverage interval) and in the runout is computed as 2.3 µm within the 95% of coverage interval. The future work will focus on investigating the influence of the machine tool runout on tool monitoring measurements and comparing the performance of the optical instrument for on-machine and off-machine instances.

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